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Initial Estimate of the $^{237}U(n,f)$ Cross Section for $0.1 < E_n(\mathrm{MeV}) < 20$

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Initial estimate of the ^{237}U(n,f) cross section for $0.1 < E_n$ (MeV) ≤ 20

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In response to a request for a ^{237}U(n,f) cross section evaluation up to $E_n = 20$ MeV, we have married a data set from our previous reliable estimate [1–3] of the cross section up to $E_n = 2.5$ MeV, to an estimate of the remaining cross section up to $E_n = 20$ MeV, deduced from simple physics arguments. This straw-man, work-in-progress estimate of the ^{237}U(n,f) cross section is intended to be used in sensitivity-test comparisons to other evaluations of the cross section (e.g., ENDF/B-VI [4] and ENDL [5]). The simple approach used in this work to generate a consistent cross section up to $E_n = 20$ MeV is validated using the well-known ^{235}U(n,f) cross section as a test case (see Fig. 1). The corresponding estimate of the ^{237}U(n,f) cross section is plotted in Fig. 2 and listed in Table I.

In a separate report [6], our ^{237}U(n,f) cross section estimate in the $E_n = 0.1 - 2.5$-MeV range, which is deduced from surrogate-reaction data, has been folded with a "tamped flattop" neutron flux, and normalized to the ^{235}U(n,f) integral cross section. The value of this ratio agrees within experimental uncertainties with the measured value [7]. The same integral cross-section ratio extracted using the ENDL evaluations for the ^{237}U(n,f) and ^{235}U(n,f) cross sections exceeds our result and the measured value by 75%.

A more sophisticated approach, taking proper account of level densities and pre-equilibrium processes, is planned to produce a reliable and robust ^{237}U(n,f) cross section estimate up to $E_n = 20$ MeV.

The ^{235}U(n,f) cross section

The ^{235}U(n,f) cross section plotted in Fig. 1 was estimated using the formula

$$\sigma_{(n,f)}(E_n) = \sigma^{(1)}_{(n,f)}(E_n) + \sigma^{(2)}_{(n,f)}(E_n) \times \left[1 - \frac{\sigma^{(1)}_{(n,f)}(E_n)}{\sigma_{CN}(E_n)}\right] \times \left\{1 - P_{pe}(E_n) \times \left[1 - P_{pe,f}(E_n)\right]\right\}, \quad (1)$$

where $\sigma^{(1)}_{(n,f)}(E_n)$ is the first-chance fission cross section, consisting of our previous data continued by a linear extrapolation up to $E_n = 20$ MeV, and $\sigma^{(2)}_{(n,f)}(E_n)$ is the second-chance fission cross section. The second-chance fission cross section is reduced, 1) by a factor that removes that fraction of the compound-nucleus cross section lost to first-chance fission, and 2) by a second factor to remove those pre-equilibrium events (characterized by the probability P_{pe}) that leave the residual nucleus with an excitation energy below the fission barrier (characterized by $1 - P_{pe,f}$).

In the range $0.1 < E_n$ (MeV) ≤ 2.2, we have used our previous results [1–3] for the first-chance fission. We have extended these results to $E_n = 20$ MeV by assuming a linear dependence of the first-chance fission cross section on the incident neutron energy. The slope of the line is taken to be the same as in the ENDF/B-VI evaluation [4] over the $E_n = 2 - 5.5$-MeV range. The intercept is fixed by matching the line at $E_n = 2.2$ MeV to the average ^{235}U(n,f) cross section for $E_n = 1 - 2.5$ MeV (1.23 barns) deduced in our previous work [1].

The second chance fission, which corresponds to fission of the ^{235}U compound nucleus, is simulated by using the well-known ^{234}U(n,f) cross section [4], shifted in neutron energy to match the excitation energy that would be populated in the ^{235}U(n,n') reaction:

$$\sigma^{(2)}_{(n,f)}(E_n) \equiv \sigma^{(2)}_{(n,f)}(A, E_n) = \sigma_{(n,f)}(A-1, E_n - B_n(A) - \Delta E), \quad (2)$$

where we've explicitly written the dependence on the target nucleus, represented by its atomic mass A. The quan-

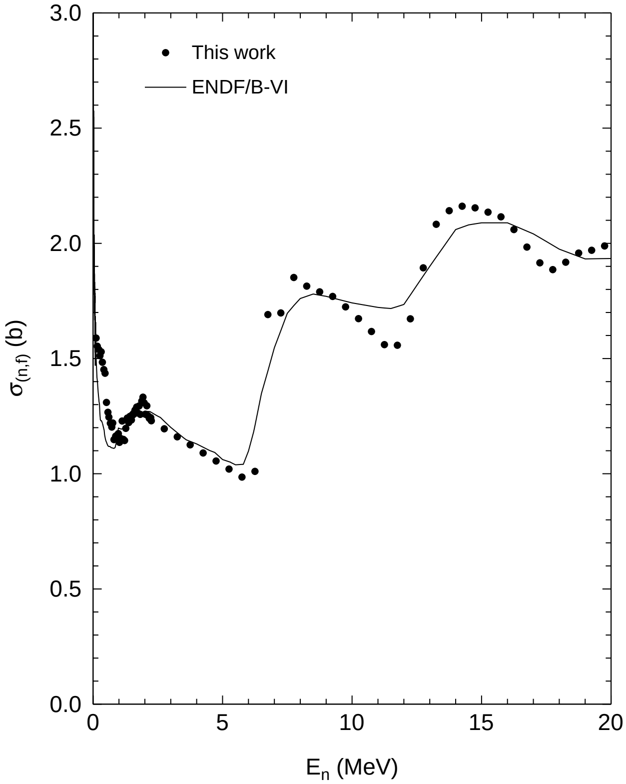

FIG. 1: Estimated ^{235}U(n,f) cross section, compared to the ENDF/B-VI evaluation.

tity ΔE represents the kinetic energy lost by the neutron emitted in the ^{235}U(n,n') reaction, and the binding energy is $B_n(235) = 5.298$ MeV. In practice, the neutron energy shift $-B_n(A) - \Delta E$ was adjusted to produce the best fit to the ENDF/B-VI ^{235}U(n,f) cross section, from which a value $\Delta E \approx 0.70$ MeV was deduced. The experimental ^{234}U(n,f) cross section used in Eq. (2) includes an implicit contribution from third-chance fission, but no correction has been made for pre-equilibrium effects in the ^{235}U$(n,2nf)$ channel.

The probability of a pre-equilibrium neutron emission $P_{pe}(E_n)$ was calculated using the code DDHMS [8]. The fraction of pre-equilibrium leaving the residual nucleus ^{235}U with an excitation energy above the inner fission barrier height $E_A = 6.00$ MeV [9] was deduced from the centroid $\overline{E}_x^{(pe)}$ and standard deviation σ_{pe} of the population after pre-equilibrium emission predicted by DDHMS, by assuming a Gaussian population distribution,

$$P_{pe,f}(E_n) = \frac{1}{\sqrt{2\pi}\sigma_{pe}} \int_{E_A}^{\infty} dE_x \, e^{-\frac{(\overline{E}_x^{(pe)} - E_x)^2}{2\sigma_{pe}^2}}. \quad (3)$$

The estimated ^{235}U(n,f) cross section in Fig. 1 is in good agreement with the ENDF/B-VI evaluation, with localized deviations of 20% or less.

The ^{237}U(n,f) cross section

The procedure tested with the ^{235}U(n,f) cross section was applied to the ^{237}U(n,f) case. Our previous (n,f) results [1–3] were used for $0.1 < E_n$ (MeV) ≤ 2.5. These first-chance fission results were extrapolated with a linear function of E_n whose slope was taken to be the same as in the ENDF/B-VI evaluation for the ^{237}U(n,f) cross section in the $E_n = 2 - 5.5$-MeV range. The linear extrapolation is flatter than in the ^{235}U(n,f) case. To lowest order, the slope of the first-chance fission cross section is a function of the difference between the barrier height and the neutron binding energy [10]. That energy difference is larger in the case of ^{237}U(n,f) compared to ^{235}U(n,f), and simple statistical arguments confirm that the first-chance fission cross section should be flatter for the ^{237}U(n,f) reaction [10].

The second-chance fission was simulated using the well-known ^{236}U(n,f) cross section [4] with a neutron energy shift, $-B_n(237) - \Delta E$, and using the value $\Delta E = 0.70$ MeV determined in the ^{235}U(n,f) case. Corrections for pre-equilibrium neutron emission were applied as in Eq. (1), using the code DDHMS. The inner fission barrier height $E_A = 6.30$ MeV [9] was used in Eq. (3).

The estimated ^{237}U(n,f) cross section is plotted in Fig. 2, and given explicitly in Table I. The ENDF/B-VI and ENDL [5] evaluations are in good agreement with each other above $E_n \approx 5$ MeV, but differ significantly at lower neutron energies. The cross section estimated in this work does not agree well with either evaluation, especially for $E_n \leq 5$ MeV.

TABLE I: Estimated ^{237}U(n,f) cross section.

E_n (MeV)	$\sigma_{(n,f)}(E_n)$ (b)
0.15	0.62
0.20	0.58
0.25	0.57
0.30	0.55
0.35	0.56
0.40	0.54
0.45	0.53
0.50	0.54
0.55	0.55
0.60	0.53
0.65	0.54
0.70	0.55
0.75	0.55
0.80	0.57
0.85	0.51
0.90	0.51
0.95	0.49
1.00	0.47
1.05	0.48
1.10	0.45
1.15	0.48
1.20	0.48

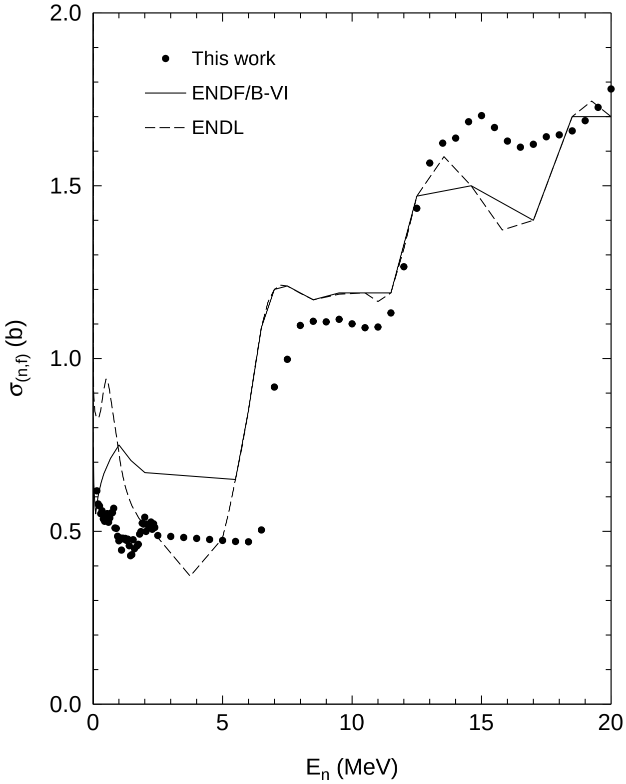

FIG. 2: Estimated ^{237}U(n, f) cross section, compared to the ENDF/B-VI and ENDL evaluations.

TABLE I: (Continued).

E_n (MeV)	$\sigma_{(n,f)}(E_n)$ (b)
1.25	0.48
1.30	0.47
1.35	0.48
1.40	0.46
1.45	0.43
1.50	0.43
1.55	0.48
1.60	0.45
1.70	0.46
1.75	0.46
1.80	0.49
1.85	0.50
1.90	0.52
1.95	0.52
2.00	0.54
2.04	0.50
2.09	0.52
2.14	0.52
2.19	0.52
2.24	0.53
2.29	0.51
2.33	0.52
2.38	0.51
2.50	0.49

TABLE I: (Continued).

E_n (MeV)	$\sigma_{(n,f)}(E_n)$ (b)
3.00	0.49
3.50	0.48
4.00	0.48
4.50	0.48
5.00	0.47
5.50	0.47
6.00	0.47
6.50	0.50
7.00	0.92
7.50	1.00
8.00	1.10
8.50	1.11
9.00	1.11
9.50	1.11
10.00	1.10
10.50	1.09
11.00	1.09
11.50	1.13
12.00	1.27
12.50	1.43
13.00	1.57
13.50	1.62
14.00	1.64
14.50	1.69
15.00	1.70
15.50	1.67
16.00	1.63
16.50	1.61
17.00	1.62
17.50	1.64
18.00	1.65
18.50	1.66
19.00	1.69
19.50	1.73
20.00	1.78

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